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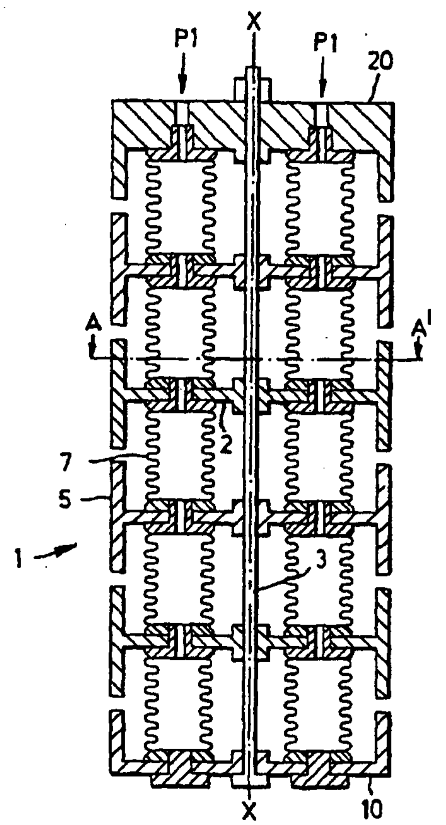
(54) Title: FLUID OPERATED ACTUATOR FOR ROBOTS



(57) Abstract: A fluid operated actuator (1) comprises a plurality of elongate parallel pressure chambers (6), each chamber comprising a plurality of individual bellows (7) connected end to end through at least one rigid connecting plate (2). Each connecting plate (2) connects a respective two adjacent bellows (7) of each pressure chamber (6) and holds the pressure chambers in laterally spaced relationship at the connecting plate (2). The actuator also incorporates a flexible tensioning member (3) to constrain longitudinal extension of the actuator. In one possible embodiment the tension member is a wire rope ligament aligned with the longitudinal axis (x) of the actuator and attached to the actuator at opposite ends thereof.

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FLUID OPERATED ACTUATOR FOR ROBOTS

The present invention relates to the field of robots and, in particular, to a new actuator for a robot.

Most devices for producing motion, such as robots, are discrete mechanisms constructed from a series of rigid links which are connected by discrete single degree of freedom joints, with an energy source provided for producing motion. Another type of robot is the serpentine robot which utilises discrete joints but combines very short rigid links with a large density of joints, creating highly mobile mechanisms which appear to produce a motion which resembles smooth curves, similar to a snake. A third type of robot is the continuum robot. Continuum robots do not contain rigid links and identifiable rotational joints. Instead, the structures bend continuously along their length via elastic deformation and produce motion through the generation of smooth curves, similar to the motion of tentacles or tongues of the animal kingdom.

The present invention relates to the field of continuum robots. More specifically, the present invention is a new fluid operated actuator for continuum robots.

Continuum actuators can be sub-divided into 'planar' or 'spatial' devices according to the type of motion produced. Planar devices only move in a single plane of bending, whilst spatial devices can bend in any direction perpendicular to their longitudinal axis.

The present invention is concerned specifically, though not exclusively, with fluid operated spatial actuators. Basic construction for intrinsic fluid operated spatial continuum robot mechanisms combine both the actuator and the supporting structure therefor into a single unit which contains no moving

parts. Operation relies on the elastic deformation of parallel actuator chambers placed at equal intervals about a central longitudinal axis. Internal fluid pressures in the chambers are controlled to generate extension forces and the structure deforms according to constraints provided by the end forms of the unit. These end forms may, for example, be in the form of rigid end plates connected to the ends of the parallel actuator chambers. The actuator chambers themselves are commonly in the form of pneumatic bellows.

Problems with existing continuum actuators include inadequate mid-span support for the parallel bellows, leading to instability. Also, mid-point translations in the bellows cause unpredictable motion. An important aspect of continuum actuators is that it is essential for operation that internal pressures generate axial extension rather than radial expansion and in many continuum actuators axial constraint is a function of the axial stiffness of the bellows walls, which can be disadvantageous. Moreover, the bellows of the continuum actuators always operate in tension due to internal pressure. Additionally, motion to return to the straight configuration of the actuator can be uncontrolled due to the material elasticity of the bellows walls. Furthermore, the maximum axial load of the actuator is a function of the material properties of the bellows. Moreover the maximum differential pressure on the actuator is limited by the stiffness of the bellows walls and their maximum elastic deflection.

A further disadvantage of existing continuum actuators is that the bellows themselves are not protected against mid-span contacts (between bellows) or from the surrounding environment. The actuators also exhibit compliant motion in the lateral direction when subjected to an external disturbing force (the device automatically returns to the undisturbed configuration upon removal of the disturbing force).

A further significant problem is that the pressure chambers of the actuator cannot be caused to shorten by the application of pressure. Shortening occurs due to the release of elastic strain energy stored in the chamber walls during a previous extension and hence shortening is a function of the mechanical properties of the chamber wall. The actuators are thus also vulnerable to permanent deformation as a result of the excessive application of internal pressure, or an undesirable interaction with the environment.

It is an object of the present invention to avoid or minimise one or more of the foregoing disadvantages.

Accordingly, the present invention provides a fluid operated actuator comprising a plurality of elongate parallel pressure chambers wherein each said pressure chamber comprises a plurality of bellows means connected end to end by connecting means provided in the actuator, said connecting means comprising at least one rigid connecting plate means formed and arranged for connecting a respective two adjacent said bellows means of each pressure chamber and for holding the pressure chambers laterally spaced apart from one another at said connecting plate means, and the actuator further includes flexible tensioning means formed and arranged to constrain longitudinal extension of the actuator.

Preferably, longitudinal extension of the actuator is controlled by the tensioning means. Optionally, the tensional force in the tensioning means may be varied so as to vary the degree of preload applied by the tensioning means on the pressure chambers. Conveniently, the actuator may therefore further include tension varying means for varying the tension in the tensioning means, preferably in real-time whilst the actuator is in operation.

The tensioning means preferably comprises a flexible member or ligament which may, for example, be a wire rope, and which is

attached to the actuator at opposite ends thereof. The flexible member preferably has a low bending stiffness and high axial stiffness. Preferably, the bending stiffness is at least an order of magnitude, most preferably two or more orders of magnitude, lower than the axial stiffness.

Optionally, when the actuator is being assembled the pressure chambers are placed into compression by applying pre-load to the flexible tensioning means. This enables the pressure chambers to be maintained in a preferred working condition throughout the range of movement of the actuator.

Each pressure chamber preferably comprises at least three or more bellows means connected end to end by at least two said rigid connecting plate means of the actuator which each connect adjacent ends of a respective two adjacent bellows means of each pressure chamber. Each said rigid connecting plate means preferably comprises a flat plate member disposed substantially perpendicularly to a longitudinal axis of the actuator, and cylindrical wall means extending parallel to said longitudinal axis of the actuator and encircling the pressure chambers. The cylindrical wall means preferably comprises a cylindrical wall member attached, preferably integrally, to a periphery of said plate member and extending in opposing directions away from said plate member. The cylindrical wall means thus limit the maximum bend which can be achieved in the actuator. It will be appreciated that the flexible tensioning means also restricts the maximum bend which can be achieved in the actuators, the extent to which the tensioning means restricts bending being dependent upon the flexibility of the tensioning means. The cylindrical wall means and flexible tensioning means thus, together, prevent over-extension and damage of the pressure chambers due to either internal pressure or external forces acting on the actuator.

Preferred embodiments of the invention will now be described, by way of example only, and with reference to the accompanying drawings in which:

Fig. 1 is a part cut-away perspective side view of a portion of an actuator according to one embodiment of the invention;
Fig. 2 is a schematic cross-sectional side view of the actuator of Fig. 1;
Fig. 3 is a cross-sectional view of the actuator of Fig. 2, taken along the line A-A′ in Fig. 2;
Figs. 4(a) to (c) are cross-sectional end views of variations of the embodiment of Figs. 1 and 2, in which different numbers of pressure chambers are used;
Fig. 5 is a perspective view of an alternative actuator using a different type of tension member to that of Fig. 1;
Fig. 6 is a perspective view of further alternative embodiment in which a further alternative type of tensioning means is used; and
Fig. 7 is a cross-sectional side view of a portion of the actuator of Fig. 2, showing the actuator bending;

The actuator which will now be described can be classified as a "fluid operated spatial actuator". Nevertheless, the actuator which is described herebelow could be designed to produce only planar motion, if desired, as will be described herebelow.

Fluid operated spatial actuators are operated by fluid pressure and consist of a plurality of parallel cylindrical bellows or elastic pressure chambers. The devices contain no moving parts and only produce motion because the pressure chambers extend when subjected to internal pressure. Generating a vector of different pressures between the chambers causes the device to deform according to the mechanical constraints provided at the terminal end forms of the actuator. The direction and magnitude of this deformation is controlled by changing the vector of applied pressures.

The prior art has all used three parallel chambers and claimed three degrees of freedom of movement i.e. bending in two planes and longitudinal extension.

The prior art use three uni-directional pressure inputs to control these three bi-directional degrees of freedom. However full control of n bi-directional degrees of freedom requires n+1 uni-directional inputs and so these actuators cannot control their full range of motion. Specifically the pressure chambers cannot be caused to shorten by the application of pressure. Shortening occurs due to the release of elastic strain energy stored in the chamber walls during a previous extension and hence shortening is a function of the mechanical properties of the chamber walls.

The new actuator described here has been designed to overcome all of the inherent problems identified in the prior art, whilst preserving the benefits of the continuum approach. This has resulted in a significantly different device to those described in the prior art.

The new actuator 1, shown in Figs. 1, 2 and 3, consists of a plurality of parallel bellows units, although unlike the prior art several shorter bellows are interconnected to form each elongate pressure chamber. The embodiment shown in Figs. 1 and 2 has six parallel chambers 6 and three pressure inputs P1,P2,P3 thereto, although many other combinations are possible using different numbers of chambers, as shown in Figs. 4(a) to (c) illustrating examples using 2, 3 or 4 chambers. Figs. 1 and 2 illustrate an embodiment using five parallel bellows sets to form the six long pressure chambers. As indicated by the arrows labelled P1 in Fig.2, each of the three pressure inputs supplies pressure to a respective two of the elongate pressure chambers 6. In the plan view of Fig.3, counting clockwise through the chambers 6 from the top of the diagram, the three pressure inputs P1,P2,P3 are connected to

the chambers in the order P1,P2,P2,P3,P3,P1. However, it will be appreciated that depending on the chamber configuration and the desired behaviour of the actuator, other combinations may be desirable e.g. P1,P2,P3,P1,P2,P3. If the total number of pressure chambers is N, then each of three pressure inputs would normally de divided into N/3 chambers. In circumstances where an actuator is designed for asymmetric performance, then each pressure input would not necessarily be divided equally among the pressure chambers 6, but in total the pressure inputs must be divided appropriately among the chambers.

The new actuator contains no moving parts.

The new actuator exhibits compliant motion when subjected to an external disturbing force in the lateral directions.

As above-mentioned, the new actuator does not use long bellows units. A modular structure has instead been developed whereby the required length of each pressure chamber is obtained from several shorter bellows 7, as shown in Fig. 2. These short bellows 7 are connected in series (i.e. end-to-end) through rigid cross sectional plates 2. Each plate connects all of the long pressure chambers together so as to prevent any relative movement between them at these connections, as well as connecting adjacent ends of two adjacent short bellows of each chamber. This increases the stability of the pressure chambers within the actuator and results in a predictable and repeatable motion.

The plates 2 are connected to the short bellows 7 by any suitable means such as screws or other metal fixings, adhesive or bonding materials. Alternatively, the plates 2 and the short bellows 7 can be moulded integrally as a single unit. An end plate 10,20 is provided at both ends of the actuator, connected to a respective end of each pressure chamber and laterally spacing apart the pressure chambers at the ends thereof.

The new actuator only produces motion with two degrees of freedom. It can bend in two planes perpendicular to its longitudinal axis X. Longitudinal extension of the actuator is prevented. Thus the actuator utilises n+1 uni-directional inputs to control n bi-directional degrees and hence there is full control of all motion.

In alternative possible embodiments, the actuator could be designed to produce motion with a single degree of freedom (planar motion) from two pressure inputs, or two degrees of freedom (spatial motion) from four or more pressure inputs.

Longitudinal extension of the actuator is controlled by inclusion of a flexible tension member in the form of a ligament 3 aligned with the longitudinal axis X of the device and only attached to the actuator at the terminal end forms of the actuator (the end plates 10, 20 in Fig. 2). Lateral movement is constrained where the tension member 3 passes through each of the cross sectional joining plates 2 but axial movement is not prevented in the current embodiment. (Although only a simple modification to the design would be required to do this).

The actuator pressure chambers are placed into compression by applying pre-tension to the flexible tension member 3. This enables the pressure chambers to be maintained in a preferred working condition throughout the range of movement of the actuator.

This flexible tension member can have a variety of forms. In the current embodiment a wire rope assembly is used. However any structure which is capable of bending whilst supporting a tension load could be used, including ropes, hoses, tubes, pipes or flexible rods. One possible alternative is shown in Fig. 5 in which the tension member is a flexible pipe 15. In Fig. 5, for clarity the cylindrical side walls (see below) of

the connecting plates are not shown. Alternatively any mechanism which can perform bending motion yet constrains or prevents longitudinal extension of the actuator could be used. Fig. 6 shows one possible arrangement in which the tensioning means is a pulley arrangement extending through all the connecting plates 2, with the pulley wheels 30 rotatably mounted on axles 35 fixed to the terminal end forms 10, 20 of the actuator.

Cylindrical walls 5 on the cross sectional plates 2 interact with the flexible tension member to limit the maximum bend which can be achieved by the actuator (see Fig. 7). Each plate 2 has its own cylindrical wall 5 parallel to the axis X of the actuator. The cylindrical walls are formed integrally in a single structure with the cross-sectional plates 2, with the plate portion of the combined structure being disposed substantially equidistantly from the ends of the cylindrical wall 5.

The cylindrical walls 5 protect the pressure chambers from direct physical contact with the environment. This increases the robustness of the actuator and allows it to be used for tasks or in environments where direct contact could occur at any point along the actuator. The prior art does not describe any form of protection for the pressure chambers within the devices.

The cylindrical walls 5 in the embodiment of Fig. 1 define a circular end cross section of the actuator. As illustrated in the embodiment of Fig. 4(a), in some embodiments of the invention the side walls 5 need not be circular in cross section, but could be another shape, for example rectangular.

The new actuator allows control of the physical design parameters of the device. It is possible to design the actuator to achieve specific performance criteria by careful selection and optimisation of the bellows units 1; the overall

spatial geometry; the tension member 3; the cross sectional plates, and the terminal end plates 10,20.

The new actuator is a stable structure producing predictable and repeatable motion. This ensures the device can be used for either open loop applications as an operator can visualise how it will move, or under closed loop control by the addition of sensors and a suitable control system. One or more sensors which measure a direct movement variable, such as a bi-axial electrogoniometer, can be included in the actuator structure, or alternatively indirect measurements and sensors for sensing selected variables, such as the chamber pressures and contact forces, could be used via predictive models of actuator behaviour, in order to monitor the actuator's motion.

Several of the actuators can be used in either series or parallel combinations to produce more complex devices exhibiting specific functionality. Potential applications for such devices include but are not restricted to:

The fingers of robot end-effectors exhibiting planar dexterity;

Positioning devices for low accuracy tasks such as inspection or spray-washing;

Operations in constrained or unstructured environments, e.g. boroscopes;

Medical uses/compliant contact with people;

Bulk delivery system which enables the shape of an enclosed hose or tube to be controlled;

Underwater propulsion systems based on fish biomechanics;

The legs of walking machines.

A prior art actuator designed by J.B.C. Davies, comprises a 744mm long pneumatic device using three parallel thin walled polymeric bellows connected at each end by rigid plates. This actuator is described in J.B.C. Davies: "An Alternative Robotic Proboscis", Proc. NATO Advanced Research Workshop on Traditional and Non-Traditional Robots, Maratea, Italy, Aug 28-Sep 2, pp 49-55, 1989, and in J.B.C. Davies: "Elephants Trunks an Unforgettable Alternative to Rigid Mechanics", Industrial Robot, vol. 28, pp 29-30, 1991. This prior art actuator was used to construct a three-fingered pneumatic gripper, each finger being one actuator. This is hereinafter referred to as the "Amadeus 1" actuator.

This table below briefly compares the design of the fingers used in the Amadeus phase 1 gripper with the design of the actuator of the present invention, which we refer to as the "Amadeus 2" actuator and the effect of the differences between the two on the operation of the actuator.

To avoid any confusion between devices the Amadeus phase 1 actuator is referred to as an "elephant's trunk" type whilst the latest design is the "continuum actuator".

Parameter	Elephant's Trunk	Continuum Actuator
Date	1996	1999
<u>Bellows configuration</u>		
No. of parallel bellows	3 parallel bellows	Plurality of parallel bellows
No. of series bellows	1 long bellows	Modular structure
No. of degrees of freedom at tip (bi-directional)	3 (Rx,Ry,Tz)	2 (Rx,Ry)
No. of control inputs (uni-directional)	3 pressure	3 pressure

Compliant motion	X - Y plane	X - Y plane
<u>Bellows support</u>		
Type	Single points with minimal mid-span support.	Multiple short bellows with intermediate spacer plates.
Effect of support on motion	Inadequate mid-span support allows instability. Bellows mid-point translations cause unpredictable motion.	This approach produces a stable structure. Mid-point translations are prevented and uniform motions are produced.
<u>Axial Constraint (Tz)</u>		
Type	Axial constraint is a function of the axial stiffness of the bellows walls.	A (flexible) tension member is located along the central axis of the actuator. This tension member prevents Tz motion independently of the axial stiffness of the bellows walls.
Bellows operational condition	Bellows operate in tension due to internal pressure.	Tension member pre-tension ensures the bellows remain in compression throughout the operating range of the actuator.

Motion to return to straight configuration	Uncontrolled motion using material elasticity of bellows wall.	Antagonistic bellows operation ensures full bi-directional control.
Maximum axial load (tension - straight actuator, incl. Hydraulic pressure)	Maximum axial load is a function of bellows material properties.	Axial tension loads are carried by the tension member.
Motion	3 degrees of freedom (Rx,Ry,Tz).	Tension member restricts motion to 2 DOF (Rx,Ry). Modelling of device motion is simplified.
<u>Bending Constraint (Rx,Ry)</u>		
Type	Bending parameters are a function of the axial and bending stiffness of the bellows material and design geometry. There are no additional bending constraints.	Bending parameters are a function of the axial and bending stiffness of the bellows material; design geometry, and the tension member. Maximum actuator bending is limited by interaction of the tension member and spacer plate design.
Maximum differential pressure	Maximum differential pressure limited by the wall stiffness of the	Maximum differential pressures limited by the working pressures of the

	bellows and their maximum elastic deflection.	bellows.
Protection	Bellows not protected against mid-span contacts.	Bellows are protected against mid-span contacts by the spacer plate design.

It will be appreciated that further modifications and improvements to the above-described embodiments may be made without departing from the scope of the invention. For example, it will be appreciated that the performance of the above-described actuator is influenced by the degree of pre-tension (sometimes referred to as "pre-load") applied by the tension member 3. Test have shown that it can be beneficial to be able to vary the degree of pre-load from zero to a specified maximum pre-load. It is envisaged that in a modified embodiment tension varying means, preferably in the form of automatic tension control means such as, for example, hydraulic or electrical control of tension in the ligament 3, could be provided to allow real-time variation of tension in the ligament. i.e. whilst the actuator is in operation.

In a further possible alternative embodiment, the ligament 3 may not be coaxial with the actuator. If the ligament is, for example, offset to a greater or lesser degree from the longitudinal axis X, it could be used to control and/or provide asymmetric bending and/or deflection characteristics in the actuator.

CLAIMS

1. A fluid operated actuator (1) comprising a plurality of elongate parallel pressure chambers (6) wherein each said pressure chamber comprises a plurality of bellows means (7) connected end to end by connecting means provided in the actuator, said connecting means comprising at least one rigid connecting plate means (2) formed and arranged for connecting a respective two adjacent said bellows means of each parallel pressure chamber and for holding the pressure chambers laterally spaced apart from one another at said connecting plate means, and the actuator further includes flexible tensioning means (3) formed and arranged to constrain longitudinal extension of the actuator.

2. A fluid operated actuator according to claim 1, wherein the tensioning means (3) is formed and arranged to control longitudinal extension of the actuator.

3. A fluid operated actuator according to claim 1 or claim 2, wherein the tensioning means comprises an elongate flexible member.

4. A fluid operated actuator according to claim 3, wherein the flexible member comprises a wire rope aligned with the longitudinal axis (X) of the actuator and attached to the actuator at opposite ends thereof.

5. A fluid operated actuator according to claim 3 or claim 4, wherein the bending stiffness of the flexible member is at least one order of magnitude lower than the axial stiffness of the flexible member.

6. A fluid operated actuator according to any preceding claim, wherein the flexible tensioning means is formed and arranged to apply pre-load on the pressure chambers so as to place the pressure chambers (6) into compression.

7. A fluid operated actuator according to claim 6, wherein the actuator includes tension varying means for varying the tension in the tensioning means so as to control the pre-load on the pressure chambers.

8. A fluid operated actuator according to claim 7, wherein the tension varying means is configured for varying the tension in the tensioning means in real-time, while the actuator is in operation.

9. A fluid operated actuator according to any preceding claim, comprising at least three said pressure chambers (6), wherein each pressure chamber (6) comprises at least three bellows means (7) connected end to end by at least two said rigid connecting plate means (2) of the actuator which each connect adjacent ends of a respective two adjacent bellows means of each pressure chamber.

10. A fluid operated actuator according to any preceding claim, wherein the actuator comprises a plurality of modules connected in series, each said module comprising one said bellows means (7) of each said pressure chamber, the bellows means in each said module being arranged in parallel and held in laterally spaced relationship from one another by a respective said rigid connecting plate means (2).

11. A fluid operated actuator according to any preceding claim, wherein each said connecting plate means comprises a substantially flat plate member (2) disposed substantially perpendicularly to a longitudinal axis (X) of the actuator, and cylindrical wall means (5) extending parallel to said longitudinal axis of the actuator and encircling said pressure chambers.

12. A fluid operated actuator according to claim 10, wherein said cylindrical wall means (5) of each connecting plate means

comprises a cylindrical wall member integrally attached to an outer periphery of said plate member 2 and extending in opposing directions away from said plate member (2).

13. A fluid operated actuator according to any preceding claim, wherein the actuator (1) utilises n+1 uni-directional pressure inputs thereto to control n bi-directional degrees of freedom of movement.

14. An actuator according to any preceding claim, wherein the actuator is a fluid operated spatial actuator (1) which can bend in two planes perpendicular to its longitudinal axis (X).

15. An actuator according to any preceding claim, wherein the actuator is a fluid operated planar actuator producing motion with a single degree of freedom.

16. A robot incorporating at least one actuator according to claim 1.

17. A robot according to claim 16, wherein the robot is a walking machine comprising legs formed from at least one actuator according to claim 1.

18. A robot according to claim 16 or claim 17, wherein the robot comprises at least one finger formed from at least one actuator according to claim 1.

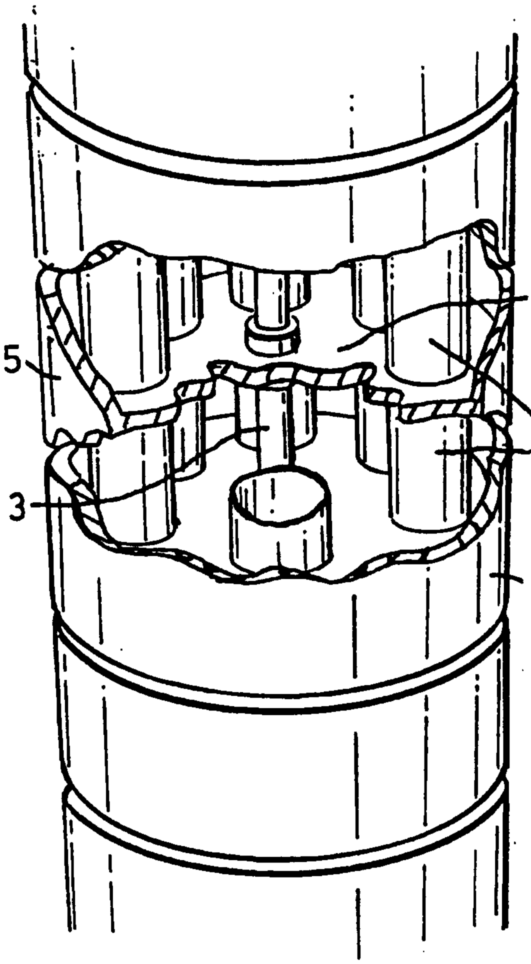

Fig.1

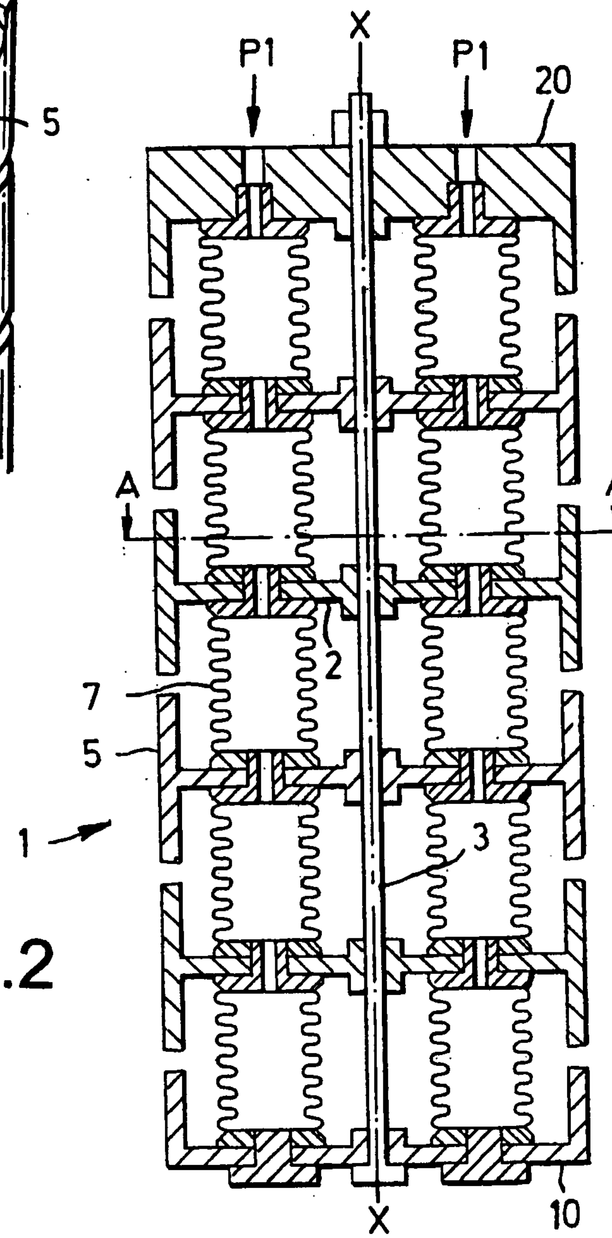

Fig.2

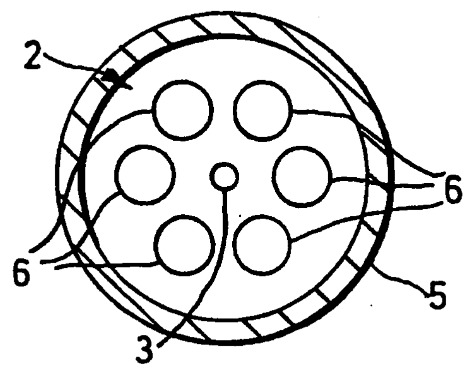

Fig.3

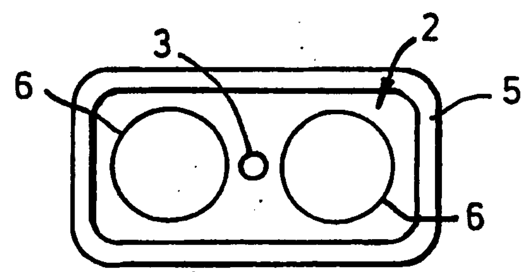

Fig.4(a)

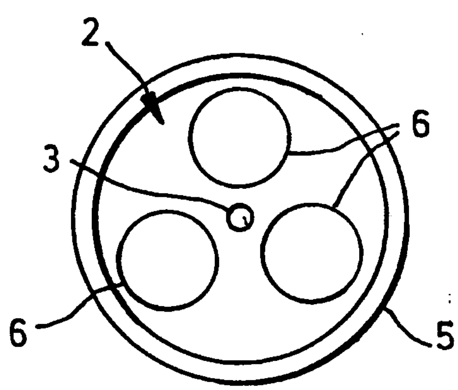

Fig.4(b)

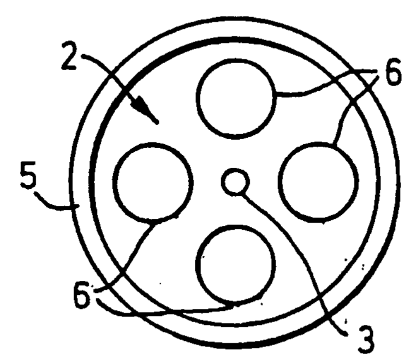

Fig.4(c)

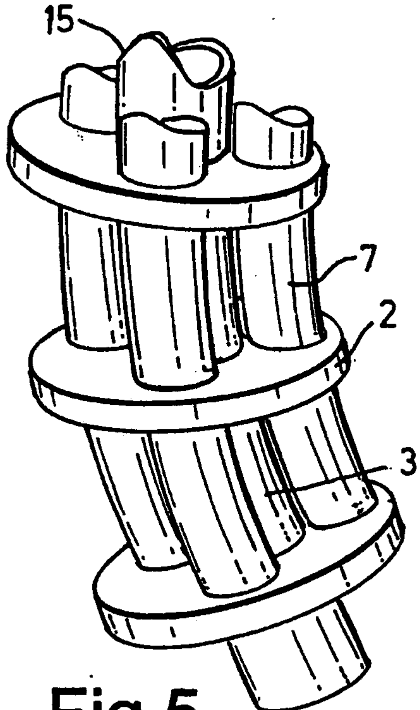

Fig.5

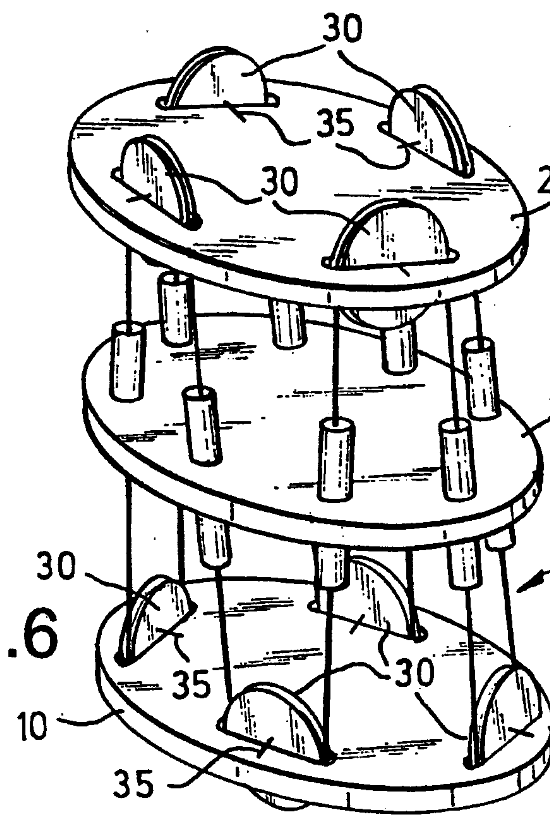

Fig.6

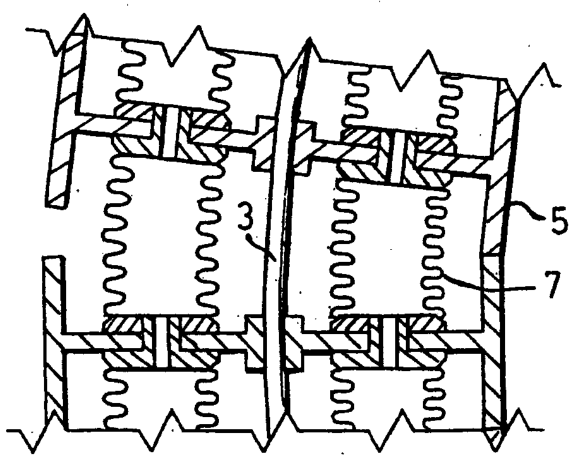

Fig.7

INTERNATIONAL SEARCH REPORT

Internat   al Application No
PCT/GB 00/03469

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 B25J18/06 B25J9/14

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 B25J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 96 35877 A (ATI ALTERNATIVE TECH INNOVATIO ;PREVISIC BRANISLAV (CH)) 14 November 1996 (1996-11-14) page 5, line 35 -page 6, line 8; claims 1,2; figures 1,10 page 7, line 32 -page 8, line 2; figure 15 page 9, line 3 -page 10, line 16; figures 18-20	1-6,9-16
Y	the whole document	7,8,17, 18
X	US 4 976 191 A (IIKURA SHOICHI ET AL) 11 December 1990 (1990-12-11)	1-6, 9-15,18
Y	column 11, line 33 -column 12, line 24; figure 23 column 15, line 10-57; figure 34	7,8,17, 18

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
11 December 2000	22/12/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Westhues, T

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